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Accumulation of Radionuclides by Plants as a Monitor System

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The accumulation of radionuclides by plants acting as a monitoring system in the environment may occur by two modes; foliar absorption by the leaves and shoot of the plant, or by root uptake from the soil. Data on plant accumulation of radionuclides may be obtained from studies of fission product radionuclides deposited as worldwide fallout, and from tracer studies of plant physiology.

The epidermal features of plant foliage may exert an effect upon particle retention by leaves, and subsequent uptake of radionuclides from the surface. The transport of radionuclides across the cuticle and epidermis of plant leaves is determined in part by the anatomy of the leaf, and by physiological factors.

The foliar uptake of fallout radionuclides, ^{90}Sr, ^{131}I, and ^{137}Cs, is described with examples from the scientific literature. The environmental half-life of ^{131}I, for example, is considerably shorter than its physical half-life because of physical and biological factors which may produce a half-life as short as 0.23/day. ^{90}Sr and ^{137}Cs are readily taken up by the leaf, but ^{137}Cs undergoes more translocation into fruit and seeds than ^{90}Sr which tends to remain in the plant part in which it was initially absorbed.

Soil-root uptake is conditioned primarily by soil chemical and physical factors which may selectively retain a radionuclide, such as ^{137}Cs. The presence of organic matter, inorganic colloids (clay), and competing elements will strongly affect the uptake of ^{90}Sr and ^{137}Cs by plants from the soil.

The role of plants as monitors of radionuclides is twofold: as monitors of recent atmospheric releases of radionuclides; and as indicators of the long-term behavior of aged deposits of radionuclides in the soil.

Introduction

The uptake and accumulation of radionuclides by plants under actual environmental conditions is a complex but challenging subject for study. The interaction of plants with radionuclides suspended in the air as particles or aerosols (and gases) or in the soil–root zone leads to accumulation and is conditioned by a multiplicity of factors, both physical and biological. The biosynthetic activity of the plant, for example, according to recent physiological studies is controlled by at least 15 to 20 basic parameters of the plant's physiology and environment. For accumulation to occur, a nominal rate of biosynthesis should take place and all of these determinant factors must be in the appropriate range.

The interactions of the plant with radionuclides occur at two levels: either in the aerial or shoot portion of the plant, or in the rhizosphere or soil-root zone of the plant (Fig. 1). Accumulation by these two modes is, as one would expect, interre-

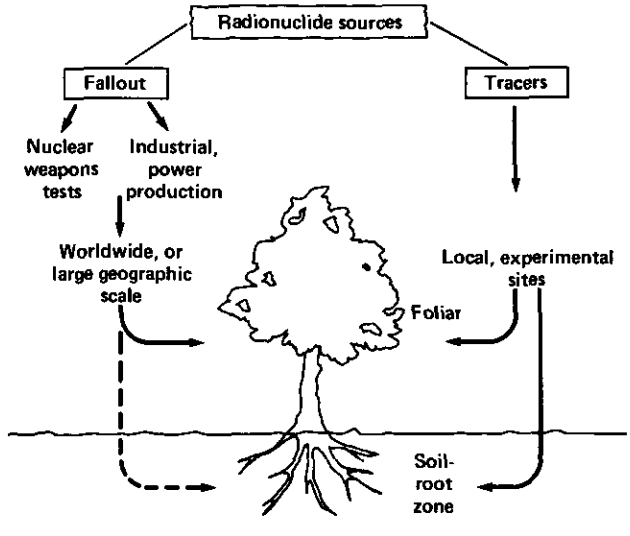

FIGURE 1. Accumulation of radionuclides by plants as a monitor system.

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lated, because radionuclides reaching the foliage and shoot of the plant will eventually be eluted or eroded from the leaves and ultimately reach the soil. The two modes are separated only in experimental studies. Under real world conditions therefore, it is usually difficult to separate the two modes of radionuclide entry into plants. This aspect of radionuclide accumulation by plants was reviewed by Russell (*1*).

During the period of fallout deposition from nuclear weapons, fresh and aged deposits of fission products with differing radionuclide composition provided an opportunity to evaluate the two modes of uptake (*2*). It was generally conceded that, during the period immediately following deposition, uptake through the foliage dominated the transfer of radionuclides by foodchains to animals or man; but in a long-term assessment, soil–root uptake may contribute from 10 to 50% of the total radioactivity reaching the consumer level of the foodchain. A recent report by Ng et al. (*3*) reviews the transfer coefficients used in predicting the transfer of radionuclides from forage vegetation to milk to man.

A strong effect is exerted by the type of plant under consideration. Algae, mosses, and lichens, in the past called cryptogamic plants, do not have true roots, stems, or leaves and absorb radionuclides deposited on their surfaces; this is typically one of their means of satisfying trace element and mineral requirements. The prominent role of lichens in the transfer of radionuclides in boreal and arctic ecosystems demonstrates the efficacy of this surface absorption of materials falling onto the thalli of these lower plants (*4*, *5*). The sensitivity of lichens to atmospheric pollution from urban or technological sources also testifies to the effectiveness of their cuticular or foliar mode of uptake and accumulation. The typical vascular plant, either graminoid, herbaceous, or woody, with conventional organs of photosynthesis, stems, and a root system shall be the basis for the discussions to follow.

Modes of Absorption and Accumulation

The first natural division of information on plant accumulation of radionuclides is between foliar and soil-root uptake by the plant. Secondly, the types of radionuclides that have been exposed to plants are essentially two kinds. First, nuclear weapons testing has in a sense labeled the biosphere with fission products, especially ^{137}Cs and ^{90}Sr, and other radionuclides with long half-lives such as tritium (^{3}H) and ^{14}C, and for varying lengths of time various

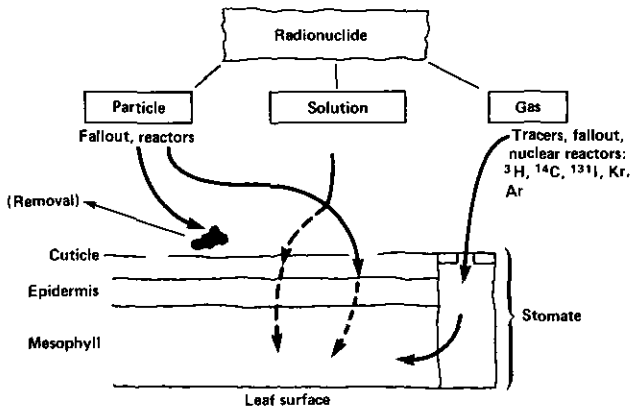

FIGURE 2. Accumulation of radionuclides by plants as a monitor system—leaf model.

activation products such as ^{54}Mn and ^{55}Fe. The persistence of the nuclear weapons radionuclides is dependent upon the residence time of the nuclear debris in the atmosphere, the physical or radiological half-life of the radionuclide, and the environmental residence time of the radionuclide in the biosphere or specific ecosystem. Some release of radionuclides occurs from nuclear power reactors but these are typically into an aquatic environment, except for gaseous radionuclides.

Our first source of information on the subject of radionuclide accumulation by plants functioning as a monitor system (Fig. 2) is from research on the fate of fallout radioactivity. Secondly, there exists a large amount of information from radiotracer experiments, some of which were designed to provide controlled data on the behavior of fallout radionuclides. Other radiotracer experiments are conducted to obtain basic physiological data on plant functions or soil-plant-relationships. Experiments using fluorescent particles (*6*) and pollen grains (*7*) to study deposition rates of particles simulating fallout also have been conducted. These data are useful, in that they describe the interaction of natural plant canopies or foliage with populations of known-size or monodisperse particles. The exposure of plants in wind tunnel facilities to monodisperse particles was conducted by Craig et al. (*8*).

Plant Foliar Surfaces

Plant foliar surfaces are covered with a variety of structures, all of which seem to have some potential in the plant's ability or propensity to accumulate radioactive or stable element particles or aerosols. Plant leaves may have any or all of the following structures that show a considerable range in their

expression, form, and density on the leaf surface: pubescence (simple, compound, stellate hairs or trichomes; pilose to lanate); glands (stalked, embedded, resinous, or salt); wax deposits (rods, plates, or spicules on the cuticle) stomata (sunken or at the surface); other structures (bulliform cells, cystoliths, or myrosin cells).

These surface features of leaves are often characteristic and constant within a plant species, and in field-grown plants may function as diagnostic criteria for taxonomic determination, as the stellate hairs of the *Cruciferae* or mustard family. A description of plant epidermal features is contained in Fahn (*9*), a text on plant anatomy.

Usually the upper or adaxial surfaces of leaves are observably different from the lower or abaxial surface in most of the features listed above, especially in the density of stomata and pubescence. Uptake phenomena are also different in upper and lower leaf surfaces.

There is also a correlation between the environment of plant growth and some of the epidermal characteristics of plant leaves. Xerophytic or desert plants have thicker cuticles and generally have features that favor water conservation, such as sunken stomata. Dense, wooly pubescence of leaves may also create another boundary layer that will affect the turbulent transfer of water vapor from the leaf to the plant microclimate and, perhaps, the deposition by impaction of particles onto that leaf surface.

All of these surface features may serve to retain particles and droplets of water containing radioactive particles or solutions, and provide the opportunity for subsequent absorption if the appropriate conditions are met. Waxy materials in general are hydrophobic and, unless some natural or man-made surfactant is present, will cause large wetting angles to occur between the water droplet and the leaf surface, reducing the contact of the surface contaminant with the leaf. Fine, dense pubescence also will cause surface tension effects and decrease the wettability of the leaf surface. Under dry deposition conditions, however, a dense mat of sericeous or lanate pubescence would entrap particles that later may be solubilized.

It is possible that a considerable amount of foliar contamination from nuclear or industrial fallout is entirely superficial and remains so in a very tightly held state. Ingestion by grazing animals will incorporate the surface-bound contaminant into the foodchain, with facilitated dissolution occurring in the acidic medium of the gastrointestinal tract.

Below the surface features of the leaf lie the structural components of the cuticle and the epidermis of the leaf, both barriers to ionic movement toward the interior of the leaf. Figure 3 illustrates the upper surface of the leaf and the features pertinent to the accumulation of radionuclides and other substances by the leaf.

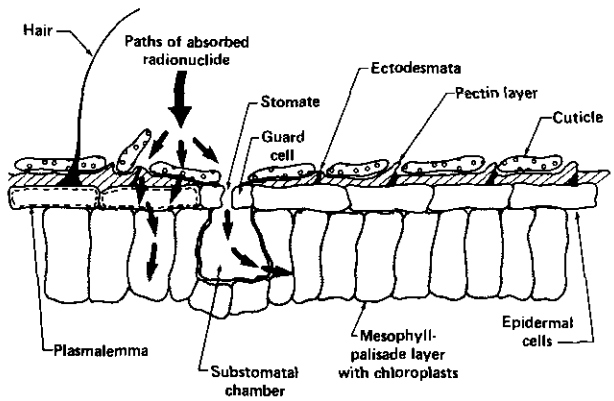

FIGURE 3. Leaf surface cross-sectional diagram. Modified from Van Overbeek (*10*).

The cuticle is essentially the interface between the leaf environment and the living structures of the leaf. It is typically made up of waxy plates, rods, spicules, or lamellae, which are embedded in a matrix of cuticular or pectic materials. The cuticular wax or cutin is a semilipoidal substance, according to Crafts and Foy (*11*), noncellular, and insoluble in most organic solvents. It covers all leaves, young stems, and the outer walls of substomatal chambers. The cuticular wax is composed of long-chain fatty acids, alcohols, and esters, which are oxidized upon exposure to air. The cuticle strongly absorbs ultraviolet radiation. The thick cuticles of alpine plants probably evolved in response to the high level of ultraviolet radiation received at high altitudes.

The cuticle is a selectively permeable membrane, cationic, negatively charged, and basically hydrophobic. In studies with chemically excised cuticles, substances move through the cuticle by simple diffusion and show a linear transport with time. Plants grown in the shade or in greenhouses or in any reduced light environment develop thinner cuticles than those of the same species grown in full sun with typical wind velocities of the unenclosed field environment impinging upon them.

The cuticular layer is usually not continuous in young leaves; even in a fully developed leaf when it is completely hydrated, the waxy plates of cutin may not form a continuous layer in some species. The cuticle is gradually eroded by wind movements of the plant after it reaches its maximum expression, but in some species it forms continuously, well into late maturity of the leaf.

Below the waxy cuticle lies a matrix of pectic materials that may extend upward through the cuticle and at the lower surface meets with the outer cell walls of the epidermal cells below. Pectin is a long chain polygalacturonic acid with numerous carboxyl side chains. It is hydrophilic, swelling upon hydration, which in some leaves will tend to separate the cuticular plates embedded in its upper surface. The pectic layer can be enzymatically dissolved and the cuticle chemically excised for study of ion movement through the first external barrier to leaf penetration of radioactive and stable elements (*12*). The significance of cuticular penetration is obvious in the use of systemic herbicides and foliar fertilizers and applications of trace elements.

The outer epidermal cell wall adjoins the pectic basement layer beneath the cuticle (Fig. 3). This cell wall is cellulosic with inclusions of pectin on the inner (epidermal) side and cutin and waves on the outer side. To be incorporated in the leaf a foliar contaminant must cross the epidermal cell wall to make contact with the plasmalemma or protoplasmic membrane of the epidermal cell. The plasmalemma of the epidermal cell is the first energy barrier to ion movement into the leaf. Protoplasmic strands called ectodesmata may extend from the outer epidermal cell walls up into the pectic layer beneath the cuticle. These strands of epidermal cell protoplasm probably play a role in the movement of substances in and out of the leaf (*13*), although the presence of protoplasm within the ectodesmata is difficult to demonstrate. The significance of ectodesmata in ion exchanges in leaves has only been appreciated in the past few years as the result of studies by Franke and others.

Transport of substances through the cellulosic wall of the epidermal cell is not impeded by any known process except adsorption onto exchange sites in or on the cell wall. The radioactive or stable ion must now cross the plasmalemma of the epidermal cell to become chemically and physiologically involved in protoplasmic pools. Bukovac et al. (*14*) recognized two phases of transport across the plasmalemma of the epidermal cell: passive diffusion into the apparent free space (AFS) of the cell walls (*15*); active transport into the protoplasm, both in a light phase and a dark phase. The radionuclide may then be accumulated in the leaf or structure in which the original absorption took place; translocated to other sites such as leaves, stems, roots, or storage organs; or distributed within the entire plant.

Table 1.

Radionuclide	Fission yield, %	Physical half-life	Radiations emitted
^{90}Sr	4.4	27.7 yr	β
^{131}I	3.1	8.0 days	β, γ
^{137}Cs	6.2	30.5 yr	β, γ

Foliar Uptake of Fallout Radionuclides

The literature on this subject is voluminous and is primarily concerned with the behavior of three fission product radionuclides, ^{90}Sr, ^{131}I, and ^{137}Cs. All of these radionuclides have gaseous precursors at the time of fission, and during the early transport from the detonation site they condense onto various sizes of particles, which at the same time fall out of the cloud at various rates. The small particles, which have large surface areas, receive worldwide distribution and incorporate much of the Sr, Cs, and I. The characteristics of these three radionuclides are given in Table 1.

Shortly after the detonation, the radionuclide composition of fallout is complex and dominated by short-lived, high-yield radionuclides. It was not possible to resolve and accurately quantitate specific radionuclides under these conditions without making radiochemical separations until the advent of the solid-state, high-resolution, γ-ray spectrometer (*16*), which took place after most of the atmospheric testing had occurred.

The biological availability of these three radionuclides in fallout is generally believed to be high; some consider them to be essentially the same as carrier-free isotopes. The surface-loaded state of the radionuclide is undoubtedly very important in determining the availability of the fallout radionuclide, which was often assessed by its solubility in distilled water.

The deposition of fallout onto vegetation may occur in two modes: wet deposition in precipitation and dry deposition without rainfall. In dry deposition, the particles either fall onto the vegetation by sedimentation or are impacted through the foliage by the mesoscale winds. The measure of deposition efficiency is termed the deposition velocity V_g, which is defined as:

$$\text{Deposition velocity } V_g \text{ [cm/sec]} = \frac{\text{Deposition rate [pCi/cm}^2\text{-sec]}}{\text{Concentration above surface [pCi/cm}^3\text{]}}$$

Vaughan (*17*) used an interception coefficient, which was defined as follows:

$$\text{Instantaneous rate of radioactive deposition } [d/dt\ (C_v)] = f V C_a, \text{ on plant leaf}$$

where f = proportionality constant (cm²/g), v = deposition velocity (cm/sec), and C_a = air concentration (μCi/cm³).

The deposition velocity and interception coefficient vary over a considerable range, and various experiments (*17*) show that these values are sensitive to particle size, environmental factors, and plant leaf characteristics. Measurements made at the Nevada Test Site indicate that particles larger than 40 μ are not likely to be retained on plant leaves. Larger particles may lodge tenaciously in leaf axils, leaf sheaths, and bases of grasses, but most particles produced by desert detonations and intercepted by vegetation were in the range of 0.5 to 5.0 μ (*18*).

Leaf cuticle and epidermis anatomy may strongly effect the retention of small particles in the size class typically retained. The pectic layer below the cuticle is not completely covered by the waxy cuticular plates in the young stages of growth and would provide more surface area for the retention of small particles with subsequent uptake when wetted by precipitation, dew, or condensation. In plant stands of uneven age, as is the rule in most natural vegetation, differences in age-related cuticular and epidermal features could introduce considerable variation in accumulation and uptake exhibited by that stand of vegetation. When the variability among species is taken into account, it is somewhat surprising that the values obtained from early field measurements were as close as they were.

After the particle is deposited on the leaf, the interaction with its structure, atmospheric moisture, and particle characteristics takes place.

Iodine-131

The behavior of ^{131}I provides a good example of the effect of plant accumulation of a radionuclide that has considerable biomedical significance because of the concentration of this element in the thyroid gland and the ease with which it enters agricultural foodchains. The rapid transport of ^{131}I through the grass→cow→milk→man foodchain is caused primarily by the interception efficiency of typical pasture vegetation for the radionuclide, the unique secretion of iodine into milk by the cow, and the rapidity with which milk is processed and reaches the consumer. Under a home farm economy, the transfer is even more rapid than by conventional food processing for public consumption. The transport of ^{131}I through the various steps of the foodchain was described by Bryant (*19*), Chamberlain and Chadwick (*20*), and Bergström (*21*).

^{131}I reaches the plant foliage primarily as a surface-loaded entity on fine particles (*22*) or in a gaseous state. Deposition onto vegetation is strongly influenced by the presence of precipitation, and deposition velocities are typically given as either wet or dry values. Absorption of ^{131}I by leaves may take place either through the cuticle and epidermis, or, in the case of gaseous iodine, through the stomata (*14*). The absorbed ^{131}I then enters organic pools within the plant and is translocated to the shoot or root.

^{131}I deposited onto plant foliage disappears at a rate faster than the physical half-life of the radionuclide (0.086 day). Factors producing this short environmental half-life, as short as 0.23 day (*23*), are wash-off by precipitation, physical loss of absorbed particles, uptake and translocation within the plant, and revolatilization. If grazing occurs, another removal process is effective in the environment. Reviews of data on the environmental behavior of ^{131}I by Thompson (*24*) and Chadwick and Chamberlain (*25*) indicate that the effective environmental half-life on grass consumed by cows will be between 0.1 and 0.2 day. Differences in vegetation type and productivity, natural versus agricultural species, grazing practices (*26*), and climate may cause variations in this value.

Although the radiological half-life of ^{131}I is relatively short, the rapid transfer of radioactivity via agricultural foodchains and essentially the quantitative absorption of iodine by the thyroid gland in man makes this radionuclide a serious radiobiological hazard in a release of fission products in dairying regions. Plants are often the most effective monitors of the presence of ^{131}I in an environment after a release, and in the absence of conventional air sampling instrumentation, provide a good assessment of environmental ^{131}I levels after accidental releases. Remedial measures such as the use of stored or covered forage and the diversion of milk into the manufacture of stored diary products such as cheese have been suggested.

Strontium-90

^{90}Sr excited considerable interest and concern during the period of fallout deposition because of its long physical half-life, its chemical and biochemical behavior, and its localization in man in a radiobiologically sensitive tissue, primarily in the bone. ^{90}Sr and its important foodchains are described by Comar and Lengemann (*27*), and, in contrast to ^{131}I foodchains, transfer to man occurs by several ecological and dietary modes. In addition to the prompt transfer of ^{90}Sr to man from surface contamination of field-grown plants (Table 2), there is also a long-term component that reaches man from the soil via root uptake. Soil uptake is generally not a significant mode of uptake for ^{131}I because, during storage time in the soil, the physical decay of the initial deposit reduces the concentra-

Table 2. Comparative foliar absorption of ^{90}Sr by several plant species.[a]

Plant species	Portion absorbed in 72 hr, %
Bean	24.2
Cauliflower	15.4
Radish	12.1
Lettuce	10.3
Corn	1.9

[a] Data of Bukovac et al. (*14*).

tions to a low level. The long-term component for soil uptake of ^{90}Sr is strongly influenced by the pedological or agronomic characteristics of the soil and any agricultural practices taking place, such as liming.

^{90}Sr is deposited in a similar way to ^{131}I, namely as a surface absorbed material on the primary fallout particles. It has been estimated to be 95% available in water from fallout particles. ^{90}Sr is most likely washed or eluted from the primary particles by precipitation or dew, and contact is thus made with the cuticle and epidermis of the leaf. Uptake through the epidermis occurs by both active and passive transport, and ^{90}Sr moves into the biochemical pools of the leaf. Translocation is not particularly effective for ^{90}Sr, and it usually remains for the most part in the leafy portions of the plant where it was originally absorbed. Uptake by active transport is associated with biosynthetic processes such as oxidative phosphorylation. When these processes are blocked with metabolic inhibitors, ^{90}Sr uptake by the leaf is reduced.

Passive transport of ^{90}Sr into the leaf may occur also and is affected by other cations that compete for sites on exchange compounds. ^{90}Sr uptake as well as stable strontium behavior shows a strong relationship with calcium pools within both plants and animals. According to Comar and Wasserman (*28*), strontium uptake related to the levels of total alkaline earths rather than to calcium alone. This suggests a nonspecific competition for sites either on exchange compounds in passive transport, or on carrier compounds in active transport.

^{137}Cs has been measured in more biological materials and soil than any other fallout radionuclide. Three isotopes of cesium, ^{134}Cs, ^{136}Cs, and ^{137}Cs, have been identified in worldwide fallout, but the 30-yr ^{137}Cs with its fission yield of 6.2% is the most prominent and significant to radiobiological problems in the environmental behavior of fallout radionuclides. The relative ease with which it enters lower plants and vascular plants has allowed many investigators to use either type of plant as relatively sensitive monitors of ^{137}Cs in the environment.

^{134}Cs is primarily produced by activation of stable cesium in the soil in the detonation area and has a much shorter physical half-life of 2.3 yr. The gaseous precursors of ^{137}Cs are present in the fallout cloud for several minutes after fissioning and subsequently are surface deposited onto particles within the cloud that is undergoing sedimentation and transport. This physical form of ^{137}Cs in fallout contributes to the high level of availability of the radionuclide as it re-enters the surface environment by sedimentation, diffusion, or impaction upon vegetation or onto the soil.

^{137}Cs is taken up readily from fallout particles deposited upon the foliar surfaces of vascular plants, lichens, and mosses, and has entered the foodchains and biota of every biome in easily detected levels as the result of worldwide distribution of nuclear weapons debris. The primary mode of entry in temperate regions is apparently foliar absorption. Gustafson (*29*) in comparing ^{137}Cs levels in the diet and in man during the period 1961 to 1968 demonstrated the dependence of dietary concentrations upon deposition rates, with a lag of about 1 yr due to the delay in processing and consumption of foodstuffs. The primary dietary constituents containing ^{137}Cs were milk, grain products, and meat, all of which are contaminated primarily by foliar uptake by forage plants and grain crops during growth.

The uptake of ^{137}Cs from soils is reduced in most aluminosilicate soils because it is fixed selectively by inorganic colloids or clays in a nonexchangeable manner. If ^{137}Cs is present in the soil solution, it is taken up with potassium by the plant root. In tropical atoll soils at Enewetak and Bikini where nuclear weapons tests took place, ^{137}Cs is highly available because the soils are composed of weathered coralline and algal limestone and the clay colloids usually present in aluminosillicate soils are absent. In these high calcium and carbonate soils, ^{137}Cs is primarily held by the organic colloids or the humic matter in the soil. The usual relationship in temperate regions of high availability of ^{90}Sr and low ^{137}Cs is thus reversed in the atoll ecosystem (*30, 31*).

In northern ecosystems, such as taiga and tundra, high organic matter, soil factors such as low pH, and the prominence of slow, continuously growing lichens and mosses in the plant biomass has produced a uniquely high accumulation in the biota and man (*32*) in regions that have not received particularly heavy deposits of fallout.

Cesium-137 is absorbed rapidly by the leaf and is distributed throughout the organs of the plant, especially to reproductive structures such as seeds and fruit. As much as 8% of the absorbed ^{137}Cs may be found in green beans after a single foliar application at the *seedling* stage (*14*) (see Table 3).

Table 3. Percentage distribution of ^{137}Cs in mature bean plants (*phaseolus vulgaris*) following spraying of aerial parts with $^{137}CsCl$ at different stages of plant development.[a]

Plant development stage	Distribution of total ^{137}Cs applied, %			
	Leaves	Stems	Carpels	Seed
Seedling	88.7	2.9	5.7	2.7
Flowering	85.0	4.4	7.3	3.3
Fruiting	79.5	4.1	11.6	4.8

[a] Data of Bukovac et al. (*14*).

Table 4. Distribution of ^{90}Sr and ^{137}Cs in the fruiting tomato plant following foliar applications at flowering.[a]

Plant part	Portion recovered in plant part, %	
	^{90}Sr	^{137}Cs
Treated leaves	84.7	51.0
Mature fruit	0.2	24.4
New vegetative growth	15.0	13.8
Roots	0.05	6.8
Stems	0.05	4.0

[a] Data at Bukovac et al. (*14*).

Strontium-90, in contrast, applied at the same time is not translocated as effectively into structures later formed by the plant, and only 0.13% was found in the green bean at maturity (Table 4). Similar results were obtained by Middleton (*33*), who found from 0.1 to 2.0% of ^{89}Sr in edible portions of wheat, cabbage, potato tubers, and sugar beets after a single foliar application, while ^{137}Cs values were in the range of 1 to 10% in wheat, cabbage, and sugar beet, and 15 to 50% in potato tubers. Direct contamination by ^{90}Sr is the most effective by aerial deposition in the immediate situation, while with ^{137}Cs uptake and translocation a single depositional event will contaminate plant products that are formed several months after the event.

The foliar transfer of ^{137}Cs to vegetation seems to be conditioned by at least one plant physiological factor. If the plant has received a recent application of potassium fertilizer and the leaf epidermis carrier compounds have a high level of potassium, a decrease in the ^{137}Cs absorption may be seen. The sorption layer carriers in the leaf epidermis apparently have a higher affinity for potassium than for cesium (*34*).

The loss of radionuclides absorbed by foliage may also occur by leaching (*35*) caused either by rainfall or by washing the leaves in experimental situations. Chamberlain (*36*) did not consider foliar leaching to be the chief mechanism for the field loss of radionuclides after absorption had taken place. The normal exfoliation of the cuticle and cuticular waxes resulting from environmental factors and maturation of leaf tissues was suggested as a field loss mechanism under dry conditions by Moorby and Squire (*37*).

The rapidity with which ^{137}Cs is absorbed by foliar surfaces and translocated throughout the plant, the efficient gastrointestinal absorption, and its secretion into milk results in rapid foodchain transfer of this radionuclide in agricultural ecosystems. Russell (*38*) demonstrated that ^{137}Cs was transferred five times faster than ^{90}Sr from forage to milk after foliar deposition. The major difference in the environmental behavior of the two long-lived radionuclides in this context is that ^{137}Cs transfer is prompt because of its availability and mobility to and in the plant, with reduced availability later because of complexation by soil inorganic colloids. ^{90}Sr, on the other hand, is absorbed more slowly by foliage, but is taken up more easily from accumulated soil deposits.

^{137}Cs in the mammal is typically found in the soft tissue mass (*39*). However some differences, although small, are seen in its internal distribution in animals. Recent data suggest that bone may be a more significant reservoir for internal accumulation of ^{137}Cs than was originally suggested by uptake data. As long-term cycling and equilibration with environmental sources occurs, bone may assume greater importance in delivering a radiation dose to the equilibrated mammal (*30, 40, 41*).

Soil-Root Uptake of Fallout Radionuclides

The deposition of fallout radionuclides onto vegetation and soil occurs as either dry particles or in precipitation. Under actual environmental conditions, both soil and plant foliage are usually contaminated simultaneously, but the rapid transfer of radionuclides is via the foliage because of the ease of foliar uptake in most plants. Menzel et al. (*42*) using a specific activity method (^{90}Sr/stable Sr ratio), found that 90% of the ^{90}Sr in Maryland wheat grains in 1959 came from foliar deposition of ^{90}Sr.

Radionuclides eventually enter the soil in aqueous solution, depending upon their basic solubility in the fallout particle, which will depend in part on the characteristics of the detonation and the properties of the soil and geological materials that become physically involved in the explosion. The fallout particles produced in the Pacific Proving Ground tests were loose, friable conglomerates of $CaCO_3$ and NaCl crystals that were very soluble. The solubility of ^{90}Sr in fallout was described by Martell (*43*).

The fallout radionuclide reaching the soil may react with the following typical constituents of the

soil: inorganic colloids (clays of various kinds); organic colloids (humic, fulvic, and other organic complexes, as a surface coating on mineral particles or in solution); organic matter (finely divided humus); soil solution (water with dissolved substances in the soil interstitial space or on particles); inorganic materials (compounds in primary minerals or in secondary weathered minerals). All of these factors may affect the ionic milieu of the soil and any solution of dissolved substances entering it, including radionuclides. The applications of fertilizers, which typically contains elements (Ca and K) that compete with two of the most prominent fallout radionuclides (^{90}Sr and ^{137}Cs) will have profound effects upon soil radionuclide behavior and plant root uptake.

Organic matter, which can exist in many different states of decomposition, size distributions, and chemical states, has a considerable potential for ion exchange and complexation. Radioactivity and trace metals may show a strong correlation with organic matter distribution in undisturbed soil profiles.

The chemical environment of soil is complex and dynamic, and the plant usually functions as an integrating organism of the chemical characteristics of the soil system. Details on soil chemical and physical characteristics as they pertain to this subject may be found in recent texts such as that of Fried and Broeshart (*44*).

The soils cation exchange capacity (CEC), which is due primarily to exchange reactions caused by mineral and organic colloids, strongly affects the behavior of radionuclides in the soil and has been the subject of much research.

Two soil phenomena are important in the accumulation of radionuclides from soils by plants, which act as monitors of the environment. The first is the fixation of ^{137}Cs by clay minerals in a nonexchangeable form, especially in soils containing 2:1 clays, such as montmorillonite, illite, and vermiculite. In this fixation, Cs and K enter the crystalline lattice of the clay mineral and the ions are irreversibly fixed between Al and Si layers. Apparently the Cs ion is held more tightly than the K ion in this lattice because of its slightly larger ionic diameter (*45*). ^{90}Sr uptake from soils is inversely proportional to the exchangeable calcium of the soil. The ratio of Ca/Sr in the plant approximates that ratio in the soil solution.

These two chemical relationships within the soil determine in a general sense the availability of ^{90}Sr and ^{137}Cs in soil to plant uptake relationships and cause the basic differences seen between the behavior of the two radionuclides in most soil systems of the temperate region. Soils derived from unique parent materials, such as the atoll soils of the Southwest Pacific and those developing under special climatic and biotic regimes such as tundra soils underlain by permafrost, react differently with radionuclides as they enter the soil system. These reactions are often important in the transfer of radionuclides to the biota of those ecosystems.

^{131}I behavior in soil is different from either ^{90}Sr or ^{137}Cs in that it is an anion and is not retained by clays as is ^{137}Cs. Some relationships might exist between the halides present in the soil and ^{131}I. ^{131}I is apparently readily leached by precipitation or irrigational water and will move into and through the root zone of plants, with effects being exerted by the structure and texture of the soil, which will limit percolation and through-flow of soil water. ^{131}I is more mobile than either ^{90}Sr or ^{137}Cs in most soils. Most of the worldwide fallout (80%) consisting of the long-lived radionuclides was found in the upper 7 cm of the soil profile in the early fallout period (*46*).

The percolation or leaching of soil-deposited radionuclides is primarily a function of the precipitation rate with secondary effects being exerted by the structure and texture of the soil (*47*). Specific radionuclides such as ^{137}Cs may be complexed to certain fractions of the soil and show more limited movement in the soil profile. Fredericksson et al. (*48*) found that after 12 months 80% of the ^{137}Cs, ^{144}Ce, and ^{106}Ru were in the top 2.5 cm of the soil. Ruthenium isotopes may form anionic complexes and exhibit greater vertical movement than other cationic radionuclides.

Strontium-90

^{90}Sr from fallout enters the soil in a water-soluble form and reacts with the chemical and physical components of the soil so that its basic availability is changed. A fraction of the ^{90}Sr in soils after deposition was found to be nonexchangeable or unavailable to plants by the usually accepted methods of measuring exchangeable cations (*49*). Water extracts of soils yield the same ratio of ^{90}Sr to Ca as is found in plants growing on that soil (*50*). Exchangeable cation measurements on soils however indicate that Sr in soils is usually less exchangeable than Ca, and discrimination factors from 1.0 to 2.5 are obtained.

In a study of Sr and Ca relationships, Adams et al. (*51*) showed species differences in the ratio of the uptake of ^{90}Sr and Ca, with mixed grasses being higher than lettuce or alfalfa.

The organic matter content of the soil has a strong effect upon the uptake of ^{90}Sr. In both beets and radishes, the ^{90}Sr concentration, when normalized

to the soil concentration, was reduced to one-fourth to one-fifth in radish tops and to one-half in beet roots as organic matter was varied from 2.1 to 10.9% (*51*).

Mills and Shields (*52*) planted a desert grass (*Bromus rubens L.*) on contaminated soil from the Nevada Test Site and found that the grass took up slightly more than 29% of the ^{90}Sr in the soil. Nishita et al. (*53*) found that wheat leaves took up 18% of the reactor waste ^{90}Sr in a sandy loam soil, and the wheat head had 3.5% of the soil ^{90}Sr.

The significant variable in the uptake of ^{90}Sr from the soil that would determine the effectiveness of plants as monitors is the competition between Sr and Ca. Epstein and Leggett (*54*) showed that Sr and Ca are bound to roots at the same absorption sites. Data on uptake from nutrient solutions and the discrimination factors obtained from them indicate, however, that increasing calcium concentration may increase the uptake of ^{90}Sr (*55*). Several investigators suggest that this might result from the higher concentrations of Ca releasing Sr that is usually bound to non-exchangeable sites on clay colloids and making the Sr more available for uptake by the plant.

In research presently being conducted in the Marshall Islands in the southwest Pacific at Bikini and Enewetak atolls, the concentration factors in the plants for ^{90}Sr and ^{137}Cs suggest that under very high soil concentrations of Ca, the ^{90}Sr uptake is suppressed. The soils in this area are not aluminosilicate in origin, but are derived from algal and coralline limestone and made up of weathered particles of $CaCO_3$ and small amounts of organic matter. Exchange capacities are generally low. In the absence of organic matter they are in the range of 10 to 16 meq/100 g soil and up to 35 meq/100 g soil in surface horizons containing humus. Concentration factors of radionuclides observed in atoll plants, primarily ^{90}Sr and ^{137}Cs, are the reverse of those usually found in temperate regions, with higher values for ^{137}Cs and lower ones for ^{90}Sr. In the absence of clay colloids, ^{137}Cs is not held in nonexchangeable sites in the soil and is highly available for plant uptake or leaching (*31*).

The effect of soil type upon uptake of radionuclides is also easily demonstrated and is undoubtedly related to the specific chemical and physical characteristics of the soil type. The range of discrimination factors or uptake coefficients given in the literature is at least partially caused by soil type differences that involve cation exchange capacity differences and variations in clay and organic matter content. Nishita et al. (*53*) show the fraction of ^{90}Sr present in five soil types as water-soluble, exchangeable, and nonexchangeable ^{90}Sr. Water-soluble and exchangeable values varied widely in the five types studied, with higher levels in the sandy types.

^{90}Sr when taken up from the soil usually accumulates in the leaves of the plant. Seed and fruit accumulation is low, and roots have less activity than the shoots of the plant.

Cesium-137

When ^{137}Cs and ^{90}Sr are deposited onto vegetation and soil from the air as fallout particles, the ratio of $^{137}Cs/^{90}Sr$ is approximately 1.7. Thereafter, this ratio changes due to the chemical and biological effects exerted by the specific soil-plant system in which the deposition has occurred. Some broad differences in the behavior of ^{137}Cs in generalized soil types were given by Russell (*56*), and others have shown differences in availability of the two radionuclides due to local soil types (*53*).

The aluminosilicate soils of the north temperate region that are widely used in agriculture have been studied most intensely with respects to ^{137}Cs and ^{90}Sr behavior. Variations in clay content, clay types, organic matter content, and texture exert measurable effects upon ^{137}Cs behavior in soils. The retention of ^{137}Cs in soils in a nonexchangeable state is generally agreed to be due to complexation by clay minerals. In soils with low clay content, ^{137}Cs availability to the plant increases, and also the potential for leaching losses increases under those conditions. Soils of the tropics that were called lateritic may have low clay content or contain highly weathered secondary minerals that have low cation exchange capacities and low ^{137}Cs-retaining ability (*57*). Some data on radionuclide behavior in tropical soils (black loams and laterites) are given by Mistry et al. (*58*). In the lateritic soil, uptake of ^{137}Cs and ^{90}Sr by plants was significantly reduced by organic matter amendments to the soil.

Soils of the high latitudes often have high organic matter because of low rates of decomposition, and surface horizons of peat are common in boreal forests and tundra. These northern regions were shown to have unique radioecological processes by several investigators (*59, 60*).

Uptake of ^{137}Cs from the soil by plants after fallout deposition generally shows lower availability than ^{90}Sr. One of the major questions that has arisen about the long-term behavior of ^{137}Cs in soils is whether availability will increase with time as biogeochemical weathering or illuvial movements occur. A recent study by Dahlman and Van Voris (*61*) of a lake bed contaminated with ^{137}Cs in 1944 sheds some light upon the subject. The mean ratio of plant ^{137}Cs/soil ^{137}Cs in all vegetation sampled in

their study was 0.03, which was essentially the same value observed in earlier measurements. Maximum soil concentrations of ^{137}Cs were observed deeper than 22 cm with a mean depth of 14 cm in the recent study. Since the depth of sedimentation was estimated at 9 cm at the time of deposition in 1944, several other mechanisms were suggested for the present depth distribution. In this temperate ecosystem, an aged deposit of soil ^{137}Cs apparently has not increased in availability to plants with time, but it is possible that a small amount of vertical movement resulting from pedological or biotic influences has occurred.

These data of Dahlman and Van Voris (*61*) are consistent with predictions made earlier by Tamura and Jacobs (*62*) and Jacobs (*63*) that ^{137}Cs would be fixed and retained by clay minerals in this region.

Low availability of ^{137}Cs in mixed fission products applied to Hanford sandy loam was reported by Nishita et al. (*53*) with concentration factors ranging from 0.01 in stems, 0.004 in wheat heads, and 0.006 in leaves of wheat. These concentration factors are in the same range as those shown in Langham's model (*64*) for ecological transport of ^{137}Cs (0.01) and not significantly different from values reported recently by Dahlman and Van Voris (*61*).

Nishita et al. (*53*) also demonstrated the effect of soil type upon the availability of ^{90}Sr, ^{106}Ru, and ^{137}Cs. No water-soluble ^{137}Cs was found in any of the five soils used after addition of the radionuclides to the soils. Exchangeable ^{137}Cs was somewhat more available than ^{106}Ru but much less than ^{90}Sr.

These data obtained from field and laboratory studies demonstrate the biological availability of ^{90}Sr and ^{137}Cs in soil systems (Figs. 4 and 5). The general conclusion of the data from temperate region ecosystems indicates that one may expect concentration factors (plant/soil) of near unity for ^{90}Sr and values much lower for ^{137}Cs (0.01-0.006), the latter being due primarily to soil retention. Variation is expected from unique climatic, pedological, and chemical factors. Krieger et al. (*65*) conducted tracer and fallout studies in the central U. S. and reported foliar deposition values that were in agreement with the UNSCEAR (*66*) constants for ^{90}Sr, but were somewhat low for ^{137}Cs (5.7% vs. 10%). Uptake of ^{90}Sr and ^{137}Cs from the soil was also lower in these data than is typically reported (0.09 and 0.009). Depth distribution of roots and the depth of the radionuclide in the soil will also influence uptake characteristics.

Pavlotskaya et al. (*67*) reported soil-depth distribution and plant availability of ^{90}Sr, ^{144}Ce, and ^{137}Cs. The mobility of radionuclides in virgin soils in the U.S.S.R. was $^{90}Sr > ^{144}Ce$ ^{137}Cs. Humic soil horizons tend to accumulate radionuclides while gley and sandy strata allow the radionuclides to assume a less localized distribution in the soil profile.

Two examples of environments that may not conform to the general behavior of ^{90}Sr and ^{137}Cs are the arctic tundra and the Pacific atolls, which have unique soils derived from coral and algal limestone.

The data on tundra ecosystems, which may be found in the Proceedings of the 2nd and 3rd National Symposia on Radioecology (*68, 69*), the Symposium on Radioecological Concentration Processes, and scientific journals, indicates that foliar or surface deposition on the dominant, low-grading tundra vegetation (mosses and lichens) had produced in arctic foodchains an efficient transfer of ^{137}Cs to man subsisting in those regions. Fallout levels were not particularly high at these latitudes. The long-lived lichen-moss vegetation, which was recognized early to be a collector of surface-deposited materials (*70*), and the exclusive winter grazing of caribou or reindeer upon this vegetation are the important steps in this trophic transfer of radionuclides, which was documented in N. Alaska, Scandinavia, and Soviet Russia.

Soil radionuclide measurements are not common

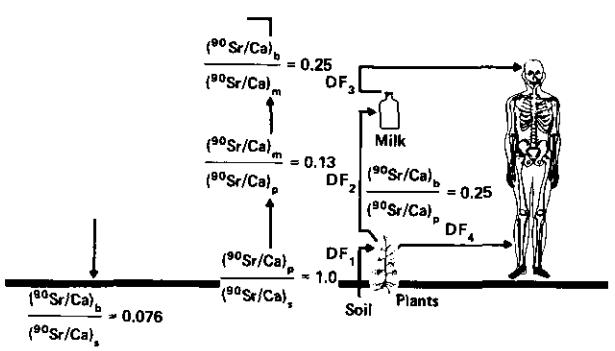

FIGURE 4. Model for ecological transport of ^{90}Sr from soils to man (U. S. diet) (*64*).

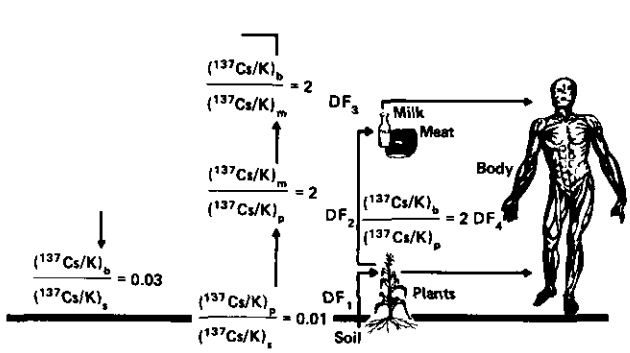

FIGURE 5. Model for ecological transport of ^{137}Cs from soils to man (U. S. diet) (*64*).

in these data on arctic ecosystems. Koranda and Martin (*71*) reported on Alaskan radionuclide measurements made in the Aleutian Islands and in coastal and interior Alaska. Soil cores taken to a depth of 17.5 cm showed that the distribution of ^{137}Cs was primarily in the surface organic layer, with low concentrations in the mineral soil below. Concentrations of ^{137}Cs below the humus-vegetation mat were in the range of 0.14 to 1.11 pCi/g dry weight. Annual plant species growing at the soil-sampling sites had ^{137}Cs concentrations from 0.36 to 1.12 pCi/g dry weight, which suggests concentration factors from 0.66 to 1.01. Recent fallout may have influenced the plant concentrations and so they may be regarded with suspicion. Small increments of fallout were received in 1968 from atmospheric tests conducted in Asia, but soil reservoirs did not seem to be affected. Low clay content and a low level weathering of primary soil minerals characteristic of northern soils may increase the availability of ^{137}Cs to plants.

The second ecosystem in which unusual soil radionuclide behavior has been recognized is the coral atolls of the South Pacific. At Enewetak and Bikini atolls, native vegetation has partially recovered in the 20- to 25-yr interim since nuclear weapons testing ceased at those locations. Recent studies (*31*) are concerned with the rehabilitation of those environments and the feasibility of utilizing plant foods produced on the islands for sustenance by the returning native people. Analyses of native vegetation, primarily two small trees, and tropical crop plants for ^{90}Sr and ^{137}Cs indicate a reversal of the usual soil availability of these radionuclides (Table 5). In the absence of any clay minerals, ^{137}Cs exhibits a high degree of availability and uptake coefficients are 100 times higher than those in temperate regions (1.3 to 5.2, $n = 125$). Cesium-137 is distributed throughout the plant biomass and is cycled rapidly among plant, litter, and soil compartments. Low potassium concentrations in the soil are undoubtedly instrumental in the conservative cycling of ^{137}Cs in the presence of 137.5 cm of rainfall per year. In contrast, ^{90}Sr in the carbonate soils containing an excess of calcium shows lower availability than ^{137}Cs, and concentration factors are typically less than unity (0.02 to 1.2, $n = 107$) (*30*).

Occasionally dramatic examples of soil radionuclide concentration by plants is observed. This occurred during the course of radioecological studies at the Nevada Test Site. Romney et al. (*72*) studied the concentration of radionuclides by plants growing at Sedan crater and used the Sedan soil materials containing many radionuclides in greenhouse studies of radionuclide uptake by alfalfa, barley, and beans. Native plants growing at the crater site

Table 5. Soil-plant uptake of ^{90}Sr and ^{137}Cs in plants and soils of Enewetak Atoll, Marshall Islands, Engebi Island.

Plant	Concentration factor (pCi/g plant)/(pCi/g soil)[a]	
	^{137}Cs	^{90}Sr
Pandanus		
Roots	23	0.9
Leaves	12	1.0
Fruit	8	0.5
Breadfruit		
Leaves	7	1.8
Fruit	7	0.8
Squash		
Fruit	26	3.0
Seeds	56	0.2
Papaya		
Fruit	8	0.4
Leaves	3	1.3
Banana		
Leaves	0.5	0.8
Coconut		
Fronds	3	0.2
Meat	9	0.03
Scaevola		
Leaves	7	0.3
Messerschmidia		
Leaves	4	0.5
Roots	—	0.6

[a] Dry weight.

such as Russian thistle (*Salsola kali*), bunchgrass (*Oryzopsis hymenoides*), and a vetch (*Astragalus lentiginosus*), had 19 radionuclides in or on their stems and leaves in 1963. Greenhouse plants accumulated 15 radionuclides, but apparently did not take up ^{91}Y, ^{102}Rh, or $^{152-154}Eu$. In January 1965, vegetation growing on the Sedan crater ejecta was surveyed by Koranda (*73*) for the presence of tritium in the biota. The samples were also analyzed for γ-emitting radionuclides with, at the time, a newly developed, high-resolution, solid-state germanium detector. Numerous unidentifiable gamma photopeaks were observed in a sample of Russian thistle, but not seen in any of the soil samples from the area. Further study of the photopeaks (*74*) showed that the gamma activity in the plant was due to the metastable isotope of ^{184}Re (160 day physical half-life), which was subsequently radiochemically separated from the plant sample for positive identification (*75*). The presence of this radionuclide in the plant when it was not detected in large samples of the soil indicated a very large concentration factor. Some desert plants have concentration factors for element such as selenium in excess of 3000.

Conclusions

The accumulation of radionuclides by plants acting as monitors may involve anatomical,

physiological, ecological, and climatic factors that will determine the deposition of radionuclides and the efficacy of the uptake, either from foliar surfaces or the soil. Details of foliar surfaces and cuticular anatomy were discussed because it is believed that their effect upon uptake is large. Some authors believe, however, that leaf laminae (blade) absorption may be insignificant (*1*) and that the leaf sheaths and the base of the plant to which eroded particles fall are the most significant plant route by which radionuclides are accumulated.

Miller (*76*), in a study of volcanic particle retention by crop plants in Costa Rica, concluded that the important factors of initial foliar retention were leaf area in the plane of particle travel, exposure of the plant part (shading effects), and the weight of the plant part relative to its surface area. The leaf surface characteristics played a secondary role in foliar deposition of particles in the series of plants studied. Absorption under damp conditions was about twice that observed under dry conditions. Leaf surface features were important according to Miller (*76*) in the fraction of small particles that were retained for long periods of weathering. These nonremoval particles were from 2 to 10% of the initial deposition. The speed with which many radionuclides are taken up by leaves may make even the larger particles held for shorter periods of time important as sources of accumulated radionuclides, depending upon their solubility.

Little (*77*) conducted studies on the deposition of 2.75, 5.0, and 8.5 μm particles onto plant leaves and soil. Leaves with surface irregularities that caused a more turbulent boundary layer favored the impaction of the 5 μm particles. Leaf hairs caused higher deposition velocities, especially in the smaller particle size (2.75 μm). There was a negative correlation between leaf area and deposition velocity, being lowest for the larger leaves. Higher wind speeds also resulted in increases in deposition velocities for the two small particle sizes. Deposition velocities for petioles and stems (or twigs) were larger than for leaf lamina, with the rougher stems having higher values. Leaf structural and anatomical features seem to play important roles in the deposition of particles onto leaf and plant surfaces where accumulation and uptake occur.

The accumulation of ^{90}Sr, ^{131}I, and ^{137}Cs by plant leaves from fallout particles occurs in significant amounts, whatever physical and biological processes are operating, and accounts for the varying levels of radionuclides transferred to man via his foodchains. During the periods of high deposition, the most effective route to man is by foliar deposition and uptake.

^{90}Sr tends to remain in the plant part in which initial absorption occurs while ^{137}Cs is redistributed throughout the plant and into reproductive structures or storage organs, which are typically eaten. ^{90}Sr contamination of grains occurs directly onto the grass inflorescence rather than by translocation to the grains from roots or leaves.

Many other radionuclides have been detected in plant foliage from fallout sources. In a study of Alaskan vegetation radionuclide concentrations, Koranda and Martin (*71*) found six radionuclides in vascular plants and lichens in most Alaskan locations in 1968 and 1970. These were ^{54}Mn, ^{95}Zr, ^{106}Ru, ^{125}Sb, ^{137}Cs, ^{144}Ce, and ^{155}Eu. The ^{125}Sb, ^{137}Cs, and ^{155}Eu were most likely from older deposits of fallout and the short-lived radionuclides were derived from recent atmospheric tests, several of which occurred in the 15 months before these collections were made. Vegetation in western U. S. often contains ^{95}Zr-Nb after an atmospheric test has been conducted in Asia. Olive leaves contained ^{95}Zr and ^{106}Ru in early 1977 in coastal California at slightly less than 1 pCi/g dry weight several months after an atmospheric test in Asia, and at a time when they could not be detected on high-volume, air-sampler filters.

The monitoring value of plant foliage (Table 6) in the event of recent atmospheric tests or releases of radionuclides from any facility has been demonstrated many times. Perennial, evergreen vegetation, whose foliage persists for more than one growing season, seem to be the most sensitive, probably because such vegetation integrate the ambient air for a longer period. Annual plants, such as grasses, will contain radionuclides that were present in their environment during the past growing

Table 6. Concentration factors derived from field measurements.

Isotope	Plant type	Concentration factors[a] Mean	Maximum	Minimum
^{137}Cs	Atoll plants	3.80	5.10	2.60
	Mixed grasses	0.052	—	—
	Pasture grasses	0.045	—	—
	Alfalfa	0.092	—	—
	Native grasses	0.14	0.24	0.052
	Native vegetation	1.70	0.43	0.056
	Desert grasses	0.016	0.25	0.006
^{90}Sr	Red Clover	7.10		
	Lucerne clover	12.00		
	Corn	2.40		
	Alfalfa-chernozem	2.00		
	Alfalfa-chestnut	2.40		
	Alfalfa-sandy	6.40		
	Alfalfa-calcareous	1.80		
	Native vegetation	4.20	6.80	1.80
	Ryegrass, loamy soil		0.50	0.49
	Ryegrass, sandy soil		20.0	12.0

[a] Ratio (pCi/g plant)/ (pCi/g soil), dry weight.

Table 7. Differences between foliar and soil-root pathways for plant accumulation of radionuclides.[a]

Foliar pathway	Soil-root pathway
Radionuclide highly available, and easily incorporated into plant tissues	Soil-radionuclide interactions occur, radionuclides compete with stable element analogs
Surface contamination may be tightly held	^{137}Cs bound to soil colliods with decreased availability
Foliar absorption in a function of fallout deposition rate	Root absorption is dependent upon cumulative deposit in soil pool and soil availability
Foliar absorption can be limited by growth factors	Root absorption takes place almost continuously from a large pool
^{137}Cs is mobile within plant, ^{90}Sr is not mobile	^{137}Cs readily re-distributed from roots; ^{90}Sr has limited mobility
Order of absorption by leaves: $^{137}Cs > {}^{140}Ba > {}^{89-90}Sr > {}^{103}Ru$	Order of absorption by roots: $^{89-90}Sr > {}^{140}Ba > {}^{137}Cs, {}^{103}Ru$
Foliage analysis valuable for determining recent radiological events which would release radioactivity into the atmosphere	Soil analysis reflects the cumulative deposition at the site, and may provide information on availability and environmental half-life

[a] Data of Bukovac et al. (*14*).

season. Epiphytic lichens are excellent monitors of air particle history, but in most urban environments they seldom survive the effects of heavy air pollution.

In the absence of recent atmospheric releases of radionuclides, the use of plants as monitors of soil deposits or reservoirs of radionuclides should be used primarily when some information on the characteristics of the soil reservoir is known. The retention of ^{137}Cs in the soil, the competition of Ca (and other salts) with ^{90}Sr, the presence of high levels of organic matter, the recycling of radionuclides by the soil biota, and the mobility of both cationic and anionic radionuclide complexes in the soil column will affect the rate at which soil uptake and accumulation of radionuclides by the plant can occur.

Recent techniques for sensitively measuring and quantitating the cumulative deposit of soil radionuclides *in situ* with mobile gamma-spectrometer systems are very useful in describing the soil reservoir of radionuclides when the depth distribution is known.

The role of plant radionuclide accumulation when no further atmospheric increments of fallout are being received will be to indicate the time-dependent behavior of the cumulative deposit or the environmental half-life or residence time. This residence time will determine the long-term dose to man from internally deposited radionuclides reaching him by known ecological transfer mechanisms.

The role of plants as monitors of radionuclides in the environment therefore is twofold: (1) as a warning system against recent atmospheric releases of radionuclides, which is capable of detecting short-lived radionuclides such as ^{131}I, the sensitive portion of the plant being the foliage because it in a sense integrates ambient air conditions; (2) as an indicator of long-term behavior and trends in aged deposits of long-lived radionuclides. Knowledge of the functioning of the ecosystem in which the deposit occurs is useful because feedback and other ecological mechanisms between ecological compartments may obscure time-dependent relationships.

With the information presently available on foliar and soil uptake and accumulation of radionuclides by plants (Table 7), the complex relationships between particles, plants, soil, and animals can be expressed with reasonable accuracy so that predictive models of radionuclide behavior in human food chains can be written with confidence (*3*).

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